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Laser Welding of Mild Steel at NIROP, Minneapolis

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A high-power laser-beam welding system has been purchased by the Naval Research Laboratory (NRL) and installed at the Naval Industrial Reserve Ordnance Plant (NIROP), Minneapolis. The purchase was funded by the Manufacturing Technology Division of the Naval Material Command. NRL acted as project manager on the purchase and installation and also provided technical expertise on laser-beam welding. The NIROP, Minneapolis, facility is an ordnance facility of the Naval Sea Systems Command; it is operated by the Northern Ordnance Division of the FMC Corporation. The plant manufactures guided-missile launch systems and gun mounts for the U.S. Navy.

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20. ABSTRACT (Continued)

The laser-beam welding system was procured from AVCO Everett Metalworking Lasers (AEML). The laser is a high-power, continuous-wave, carbon dioxide laser and can deliver 15 kW to the workpiece. The linear work station can produce either horizontal or vertical welds up to 10 ft (3.0 m) long. The beam director can place the focused beam at any position within a volume 10 ft × 10 ft × 6 ft (3.0 m × 3.0 m × 2 m). The work station has a variable traverse speed of 1.7 to 100 in./min (43.2 to 2540 mm/min).

A comparison of the time required to weld a component with the present process and of the anticipated time necessary to weld the same component with the laser beam has resulted in an economic analysis. This economic analysis indicates that a cost savings of over $500,000 per year can be realized. Three illustrations of different weld joints that will be fabricated with the laser beam are given. An example of how the laser can possibly reduce costs even more by replacing extrusions with weldments is also shown.

The mechanical properties of laser-beam weldments of A36 structural steel have been measured by transverse-tension specimens. The laser-beam weld is stronger than the base plate. Hardness traverses across the base plate and the heat-affected and fusion zones indicate an increased hardness in the heat-affected and fusion zones. This increased hardness can be modified by a stress-relief heat treatment. Charpy V-notch specimens have been used to measure the amount of energy absorbed as a function of temperature. The microstructure of the base plate is ferrite and pearlite. The heat-affected zone is refined ferrite/pearlite, whereas the fusion zone is bainite.

CONTENTS

EXECUTIVE SUMMARY

This manufacturing-technology program, laser welding of mild steel at NIROP, Minneapolis (DNS-710), developed the methods, processing data, and equipment for laser welding of mild steel. The laser-beam welding system has replaced submerged-arc welding in applications described in the report. The advantage of the laser-beam welding system is that it gives a thirtyfold increase in speed while, at the same time, it provides acceptable mechanical properties and exceptional fracture toughness. The economic analyses indicate that the laser-beam welding system will pay for itself in three years of operation on only a limited number of production pieces. This is the first high-power (15-kW) laser to be placed in production. Since the laser on-time is much less than the setup or work-station-utilization time, the laser can be time-shared among several work stations. Other manufacturing-technology programs will add work stations to heat-treat, clad, cut, and alloy.

LASER WELDING OF MILD STEEL AT NIROP, MINNEAPOLIS

INTRODUCTION

The primary concern of the Navy Manufacturing Technology program is to address problems of the production process and to increase manufacturing productivity for systems and equipment being procured by the Navy. More specifically, program objectives include the promotion and establishment of improved processes, methods, techniques, and equipment for the most efficient and economical production of defense material and provision of the technology required to advance manufacturing capability. To achieve these objectives, the Naval Sea Systems Command (NAVSEA) sponsored a manufacturing-technology program, "Laser Welding of Mild Steel at NIROP, Minneapolis." This program was administered by the Naval Research Laboratory (NRL), which also provided the technical management. The NIROP, Minneapolis, facility is the Naval Industrial Reserve Ordnance Plant, Minneapolis, a government-owned, company-operated facility which fabricates guided-missile launching systems and gun mounts for the Navy. The plant is operated by the Northern Ordnance Division of the FMC Corporation.

This manufacturing-technology program has purchased and installed a laser-beam welding system at NIROP. Through the technology-transfer phase of the program, welding engineers of FMC have been instructed in the use of high-power lasers for welding. The laser system allows us to weld mild steel efficiently, soundly, and at a much faster welding speed than the present submerged-arc welding process. The laser and the work station are described in this report. A brief description of the welding process is followed by a more detailed exposition of the properties of the weldments. An economic analysis on several different weldments is given and, finally, a preview of future work is given.

THE LASER

NRL purchased the laser-beam welding system as a result of a competitive procurement from AVCO Everett Metalworking Lasers (AEML). The laser is a continuous-wave, closed-cycle, electric-discharge carbon dioxide laser with a wavelength of 10.6 μm. Table 1 gives the characteristics of the laser.

Table 1 — Characteristics of NIROP Laser

Power output	1-15 kW (at workpiece)
Repeatability and accuracy	$\pm 3\%$
Duty cycle	Continuous (CW)
Lasing gas mix	$He:H_2:CO_2:CO$
	6:4:1:1
Wavelength	10.6 μm
Operating pressure	0.1 atm (nominal)
Welding beam	
Focal diameter	0.040 in. (1.0 mm) (f/7 focus system)
Power in focal spot	85% of laser output

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An electron-beam (e-beam) stabilized discharge provides the required pumping of the lasing mixture to generate the coherent 10.6-μm radiation. Lasing occurs in an "unstable resonator" optical cavity of the discharge region. The lasing gas is a mixture of helium, nitrogen, carbon dioxide, and carbon monoxide. A high-energy e-beam ionizes the gas, raising its electrical conductivity sufficiently to allow the main sustainer current to flow in the laser gas between the sustainer electrodes volumetrically.

The main chamber is a closed-circuit wind tunnel through which the lasing gas mixture circulates. Heat exchangers, cooled by the primary water supply, remove waste heat. Axial-flow compressors or blowers drive the lasing gas mixture through the channel where lasing occurs.

The cathode and anode are attached to opposite walls of the channel. Sustainer current flows across the gas stream between the electrodes. The ionizer injects a broad, uniformly accelerated beam of high-energy electrons into the flowing laser gas, which becomes ionized, to provide a stable, sustained discharge in the laser gas between the sustainer electrodes. In a closed-loop mode, a power monitor senses the laser output and adjusts the ionizing current, and hence the sustainer current, to maintain programmed output power.

Water-cooled copper mirrors at each end of the channel form the resonator cavity. The transfer mirror is tilted to direct the output beam at a slight off-axis slope out of the aerodynamic window. The aerodynamic window permits the laser beam to exit from the low-pressure main chamber without allowing outside air to enter the chamber.

The laser output power is controlled by the e-beam current. The basis of the output is the set point on the operating panel and the maintenance of this power setting by the power-monitoring subsystem. The time duration of the laser output is controlled by a dual-shutter subsystem sequenced by the programmable controller. The output power at the cone power meter is variable from a threshold of 1 kW to at least 20 kW. The maximum output power does not vary more than $\pm 3\%$ within a 30-min period or more than $\pm 5\%$ during an 8-h period.

The expanding beam emerging from the aerodynamic window encounters a transmissive chopper blade, which directs part of the energy to the fast detector system used for monitoring laser-power stability. The beam can then encounter a sliding mirror, which directs the beam to a cone power meter. The expanding beam is collimated and directed to a rotating mirror, which is used to direct the beam to the desired work station.

THE WORK STATION

The linear-weld station is arranged with the work-motion car moving normal to the optical axis. The track length is sized to accommodate a 10-ft (3-m)-long weld seam, and the variable-speed traverse car can move at speeds of 1.7 to 100 ipm (0.7 to 42 mm/s). Table 2 gives the characteristics of the work station.

Table 2 — Characteristics of Laser-Weld Work Station

Linear-weld work station	
Workpiece dimensions	10′ × 10′ × 6′ (3m × 3 m × 2 m)
Workpiece load	20,000 lb (9100 kg)
Work motion	1.7-100 ipm (0.7-42 mm/s)
Seam tracking	±4 in. (±10 cm) (in two axes orthogonal to weld direction)
Wire feed	Variable
Inert-gas shield	

The focusing optics are mounted on an arm on the optical support, all adjustable along the optical axis, with the arm adjustable in the elevation axis. For down-hand welding the arm is raised to the proper height to place the telescope focal point approximately at the weld elevation. The support is moved towards the work until the focal point is over the weld location. Thus, the focal point can be placed anywhere within a 10-ft × 10-ft × 6-ft (3-m × 3-m × 2-m) volume.

Linear welds can be equally well performed in the vertical plane if the down-hand mirror is removed and the optical support is adjusted away from the work car to a position where the focal point is at the weld plane. A seam tracker and wire-feeder, gas-shielding, and plasma-suppression devices are incorporated into the end of the beam director at the focal point of the laser beam.

LASER-BEAM WELDING

Thick-section laser-beam welding is achieved by a high-power laser beam focused onto the surface of an alloy. This focused, highly collimated source of heat evaporates the alloy and creates a "keyhole," or metal-vapor-filled cavity, through the thickness of the workpiece. Surrounding this keyhole is the weld pool, a volume of molten metal in dynamic equilibrium with the metal vapor. As the workpiece is moved, melting takes place at the leading edge of the weld pool and solidification occurs to the rear. The depth of penetration of the keyhole and the shape of the weld pool are governed by a variety of factors, such as the amount of energy absorbed and the amount reflected at various temperatures, the laser-beam power at the focused spot, the size of the focused spot, the travel speed, the gas used to shield the weld pool, the method of gas shielding, or the thermal properties of the alloy being welded.

At the top of the keyhole, above the workpiece, the evaporated alloy forms an ionized gas called a plasma. If this plasma is allowed to remain at the top of the keyhole, it will absorb some of the laser beam and reradiate it in all directions, thus decreasing the depth of penetration of the weld. The plasma can easily be displaced by a stream of inert gas across the top of the keyhole. Helium, because of its ionization energy, is usually used for plasma control, although a helium-argon mixture may be used effectively [1]. Thus, plasma formation is not considered to be a limiting factor in laser-beam welding.

The relative positions of the top of the plate and the focal point of the laser beam have been shown [2] to affect the penetration capability for a fixed power and speed. To fabricate the deepest welds with a high depth-to-width ratio, the focal point of the laser is usually positioned about 2.5 mm (0.1 in.) below the top surface of the plate.

EXPERIMENTAL METHOD

Process

The most practical carbon steel commercially available for welded structures is ASTM A36, which is a steel with optimum composition for strength and weldability [3]. This steel is widely used in many thicknesses and has excellent mechanical properties when welded. Welding of this alloy can be achieved by many processes, shielded metal arc (SMA), gas metal arc (GMA), submerged arc (SA), electron beam (EB), etc. The resulting weldments have good mechanical properties and ductility. Although they are not normally used in structures subjected to low temperatures or impact loading, the Charpy V-notch (CVN) energy of the welds is equal to or greater than that of the plate. In large structures, the weldments are often given a stress-relief heat treatment to minimize distortion and residual stress and to enhance fit-up.

Table 3 gives the laser processing parameters for the A36. These parameters have resulted in weldments which have yielded satisfactory mechanical properties.

Table 3 — Laser Beam Welding Process Parameters for A36 Steel

Thickness (mm)	Thickness (in.)	Power (kW)	Speed (mm/s)	Speed (ipm)	Heat Input (kJ/mm)	Heat Input (kJ/in.)
6	0.25	6	21	50	0.29	7.3
9	0.38	10	17	40	0.59	14.9
12	0.50	13	14	33	0.93	23.6
15	0.63	13	6	15	2.17	55.0
12	0.50	10	14	33	0.71	18.0

In the 12-mm-thick plates, laser-beam weldments were fabricated with two different plasma-control techniques. The usual technique for controlling the plasma is to direct a lamellar flow of gas (helium) transverse to both the weld joint and the laser beam. This technique results in a clean weld with good reinforcement. The modified technique consists of directing a narrow stream of inert gas at the interaction point in the plane of the weld joint and the laser beam. The plasma is effectively displaced forward and preheats the area in front of the interaction point. This preheating increases the amount of laser energy that is absorbed, and it reduces the laser power required to weld the plate at a fixed travel speed.

Properties

The mechanical properties (yield strength, ultimate strength, and elongation) were measured by transverse-tension specimens, either round or reduced-section plate. The mechanical property data (Table 4) reflect the base-plate values, since the specimens broke in the base plate and not in the fusion or heat-affected zones. For all of the thicknesses of plates welded, transverse-bend specimens were machined and tested. These side-, face-, and root-bend specimens were bent about the appropriate-diameter anvil [4]. Charpy V-notch specimens were machined from the A36 weldments, as well as from the base plate (L-T and T-L orientations) [5]. These specimens were tested as a function of temperature. Additional bend, mechanical-property, and Charpy V-notch testing was performed on weldments of A36 that had been given a stress-relief heat treatment at 635°C (1175°F) for one hour. Figure 1 shows the values of the Charpy V-notch energy as a function of temperature.

Table 4 — Mechanical Properties of Laser-Beam-Welded A36 Steel

Thickness (mm)	Thickness (in.)	Yield Strength (MPa)	Yield Strength (ksi)	Ultimate Strength (MPa)	Ultimate Strength (ksi)	Elongation %
6	0.25	276	40	442	64	23
9	0.38	269	39	428	62	22
12	0.50	276	40	448	65	24
15	0.63	269	39	435	63	26

Microstructures

The A36 steel has a ferrite/pearlite structure. When this steel is laser-beam welded, the heat-affected zone (HAZ) has a refined, smaller grain size, ferrite/pearlite structure, whereas the fusion zone has a bainitic structure. Figure 2 shows these microstructures. Figure 3 shows hardness traverses across the HAZ and the fusion zone for both the as-welded and stress-relief laser-beam welds.

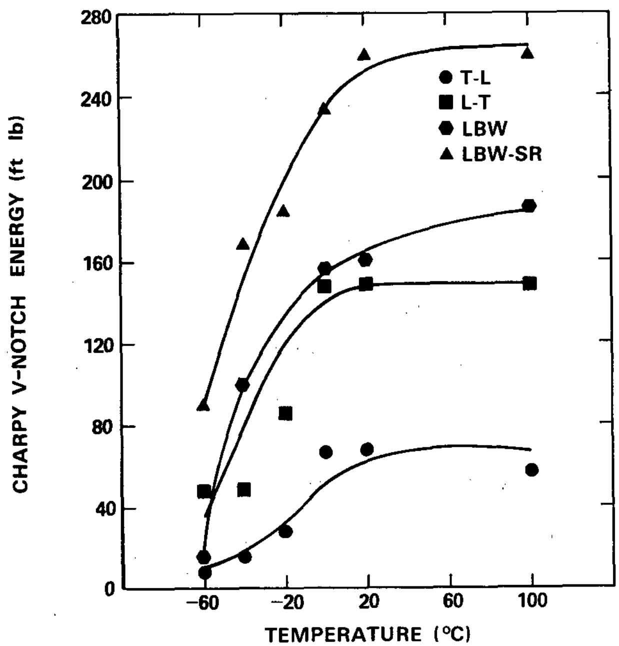
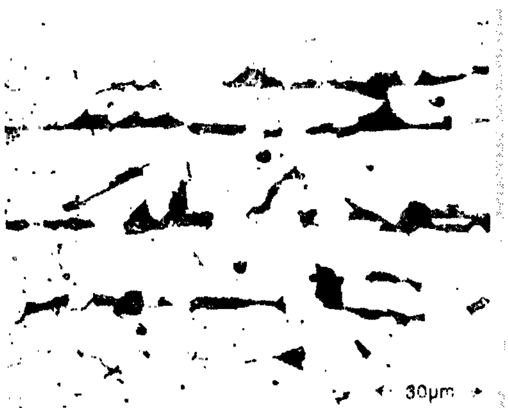
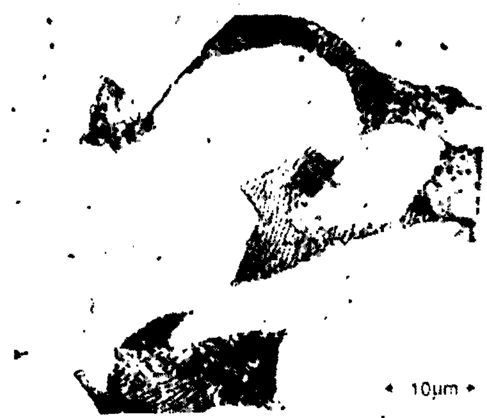


Fig. 1 — Charpy V-notch energy as a function of temperature for the base plate (T-L, L-T) and laser welds (as welded [LBW] and with stress relief [LBW-SR])



(a)



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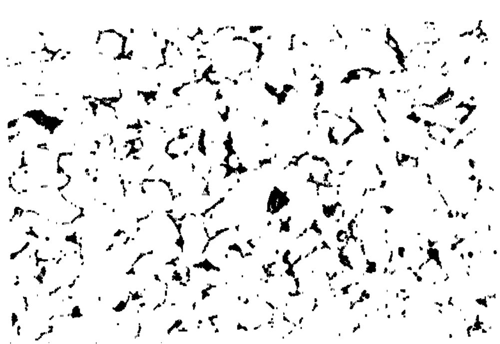
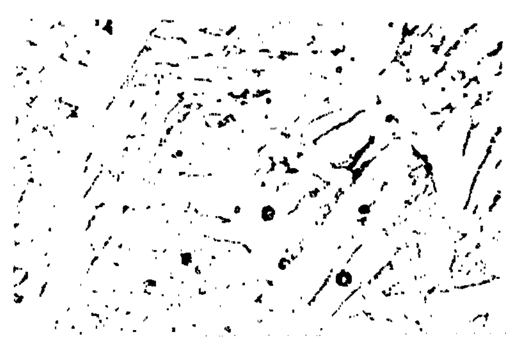




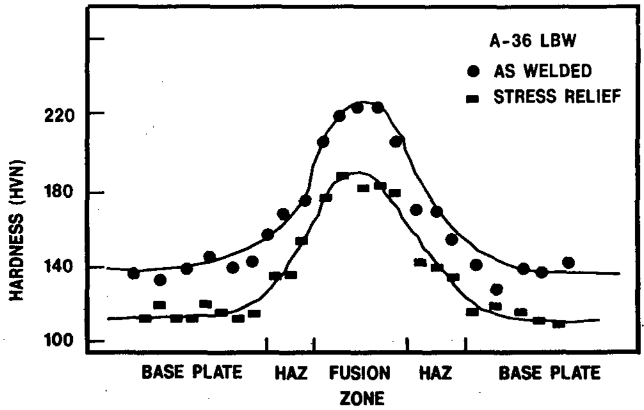
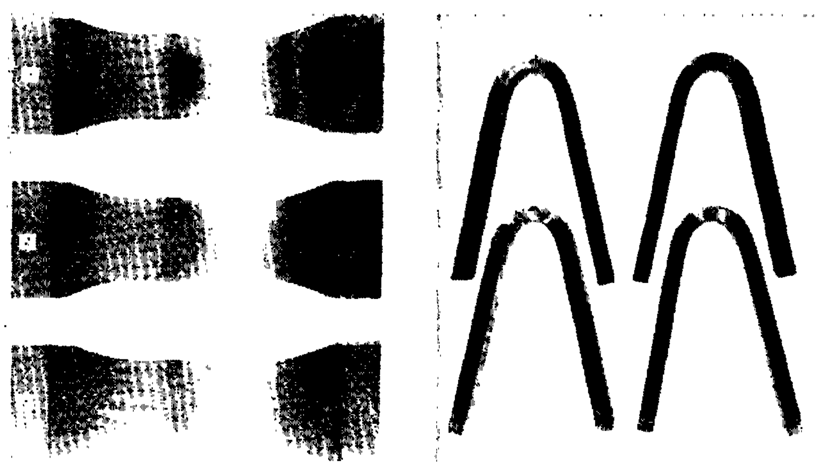


Fig. 3 — Hardness traverses across A36 laser beam weldments (as welded and with stress relief)

ANALYSIS OF RESULTS

The mechanical-property data gathered in these tests are a reflection of the base-plate properties. But they also imply that the HAZ and the fusion zone are stronger than the base plate. The bend specimens, which typically expose defects in the weldment, such as undercut and interior defects [4], satisfactorily passed their tests. A close examination of Fig. 4 indicates that the increase in hardness of the fusion zone of the A36 laser-beam welds results in a mild loss in ductility in this region. This is indicated, in both the transverse-weld tension specimens and the bend specimens, by less necking, or stretching, in the HAZ and the fusion zone than in the base plate.



(a) (b)

Fig. 4 — Macrophotographs of (a) transverse tension [σ_{ys} = 37 ksi (255 MPa); σ_{ult} = 65 ksi (448 MPa); elongation 24%] and (b) bend specimens

Considering the chemical composition of the A36 base plate, the microstructures observed in the HAZ and the fusion zone are what are to be expected from a high-energy-density, low-heat-input process. Solidification takes place very rapidly, and the heat is conducted away from the fusion zone quickly, resulting in a very rapid quench from a high temperature. The increase in hardness values in the A36 laser-beam weldments is moderate and indicates that no appreciable change in properties should occur.

The results of testing the Charpy V-notch specimens as a function of temperature are quite interesting. The base-plate specimens indicated two different levels of upper-shelf values, depending upon the specimen orientation (L-T or T-L). The as-welded laser-beam weldments have a higher upper-shelf value than those of the base plate. The stress-relief laser-beam specimens had an even higher upper shelf value (most of the specimens stopped the machine at impact) and also a higher transition temperature. The values plotted in Fig. 1, for the absorbed energy at the various temperatures, are an average of at least three tests, and of as many as five. The scatter in the energy values decreased with decreasing temperature. The Charpy requirement for an E70-type weld wire, which would normally be used to weld the A36 steel, is 27 J at −30°C (20 ft-lb at −20°F). The autogeneous laser-beam welds of A36 easily surpass that requirement.

The difference in upper-shelf values between the two directions in the base plate is a result of the directionality of the manganese sulfide stringers. A crack will propagate more easily along these stringers than across them. The difference in upper-shelf values between the laser-beam welds and the base plate can also be related to the inclusion content and shape. Fusion-zone purification, i.e., the evaporation of inclusions in the weld zone as a result of the laser-beam welding process, has been shown to reduce, significantly, the inclusion content, as well as change their sizes and shapes [6,7]. When an equivalent treatment, i.e., a reduction in the number of inclusions in a steel, is carried out as part of the steelmaking process, the properties of the steel become less anisotropic [8]. The differences in the upper-shelf values of the laser-beam welds that result from the stress-relief heat treatment are not so simply explained.

The microstructures in the fusion zone of the as-welded and stress-relief heat-treated laser-beam welds are compared in Fig. 5 for three different etches: (a) nital, (b) picral, and (c) oxalic acid. According to Samuels [9], nital develops the ferritic grain boundaries but picral does not; pearlite colonies are developed uniformly by picral but not by nital; cementite films, located at the ferritic grain boundaries, are clearly developed by picral but are difficult to distinguish after etching in nital. The oxalic acid has been used [10] to reveal prior austenite grain boundaries. Careful examination of these microstructures does not yield information as to the increase in absorbed energy in the stress-relieved welds.

The solidification structures of the welds were examined with both ammonium persulfate and nitric acid used as etchants. No noticeable differences in solidification structures were observed with the ammonium persulfate etch. A distinct center line was observed in the as-welded solidification structure with the nitric acid etch, but it was not observed in the stress-relief solidification structure (Fig. 6). A noticeable center line is often observed in laser-beam welds, since the heat flow is into the base plate and grain growth is toward the center of the weld pool. Lower-melting-point elements can easily collect, therefore, at the center line. The stress-relief heat treatment, then, must allow these elements to diffuse away.

Figure 3 showed another factor that contributes greatly to the increased upper-shelf value and lower transition temperature of the stress-relief laser welds. The stress-relief heat treatment lowers the hardness of the heat-affected and fusion zones. Since hardness can be related to strength, and as the strength increases, absorbed energy decreases [8], the lower hardness contributes to the higher upper-shelf values.

This type of phenomenon, increased absorbed energy after stress relief, has been shown to exist in arc and electron-beam welds [11,12]. Davies and Garland attribute the increase in the impact strength to the degeneration of the bainitic carbides, formed along the prior solidification boundaries, into ferrite-carbide aggregates. Russell et al. report a decrease in hardness as a result of the stress-relief heat treatment and do not report any microstructural changes. They also report a significant increase in the energy absorbed as a result of stress-relief heat treating.

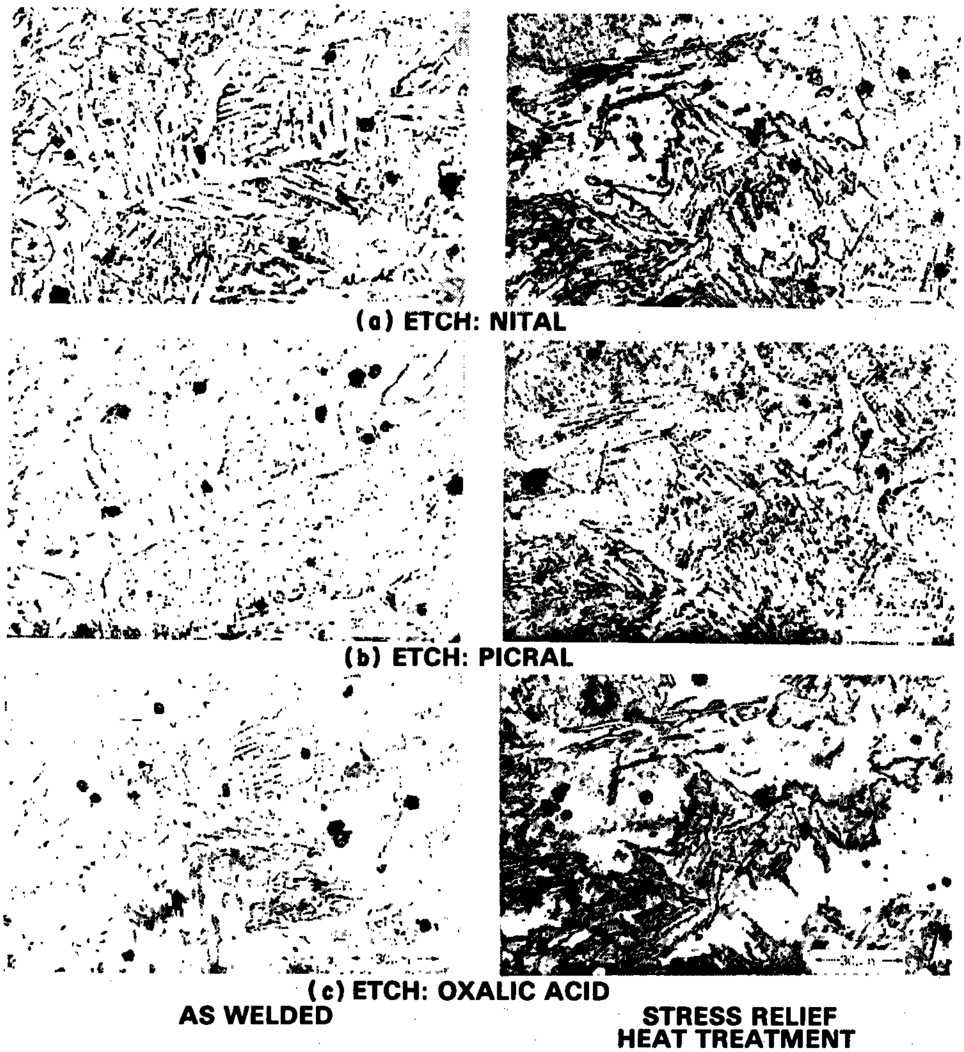


Fig. 5 — Microstructures of fusion zone in the as-welded and stress-relief conditions, developed by different etchants

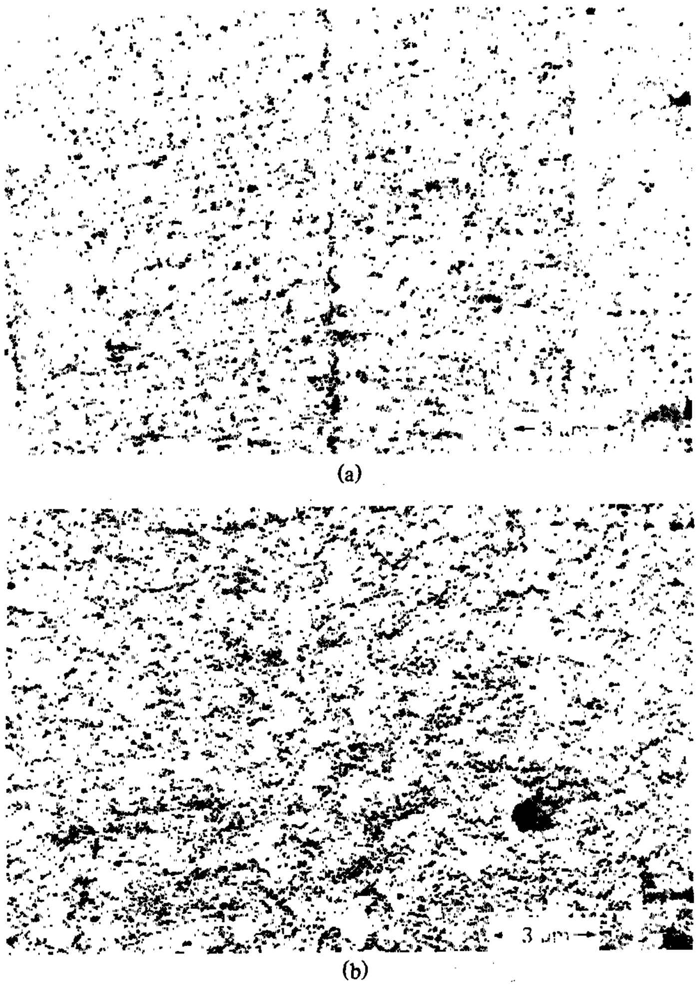


Fig. 6 — Solidification structure in the as-welded and stress-relief conditions

ECONOMICS

A comprehensive feasibility study [13] sponsored by NAVSEA at NIROP, Minneapolis, examined the cost savings of laser-beam welding over conventional welding fabrication. As part of this study, a model was constructed of weld-shop procedures. This model identified both on-station and off-station operations associated with various weld-joint configurations. Actual production-time standards were then used to estimate the time savings resulting from laser-beam welding for various generic weld joints. As anticipated, the major time savings were derived from a reduction in burn-time, i.e., the time during which the arc is struck in conventional welding or the beam-on time in laser welding. Significant time savings also resulted from reduced straightening (less distortion) associated with laser-beam welding.

The FMC Corporation, under contract with the Navy, developed an integration plan [14] for the laser-beam welding system. A detailed analysis of weldments to be fabricated by the system was completed. Three examples are considered.

The first example is the welding of the Mark 6 strikedown and hoist tubes. As shown in Fig. 7, the tubes comprise the main structure in the material-handling mechanism for loading and unloading

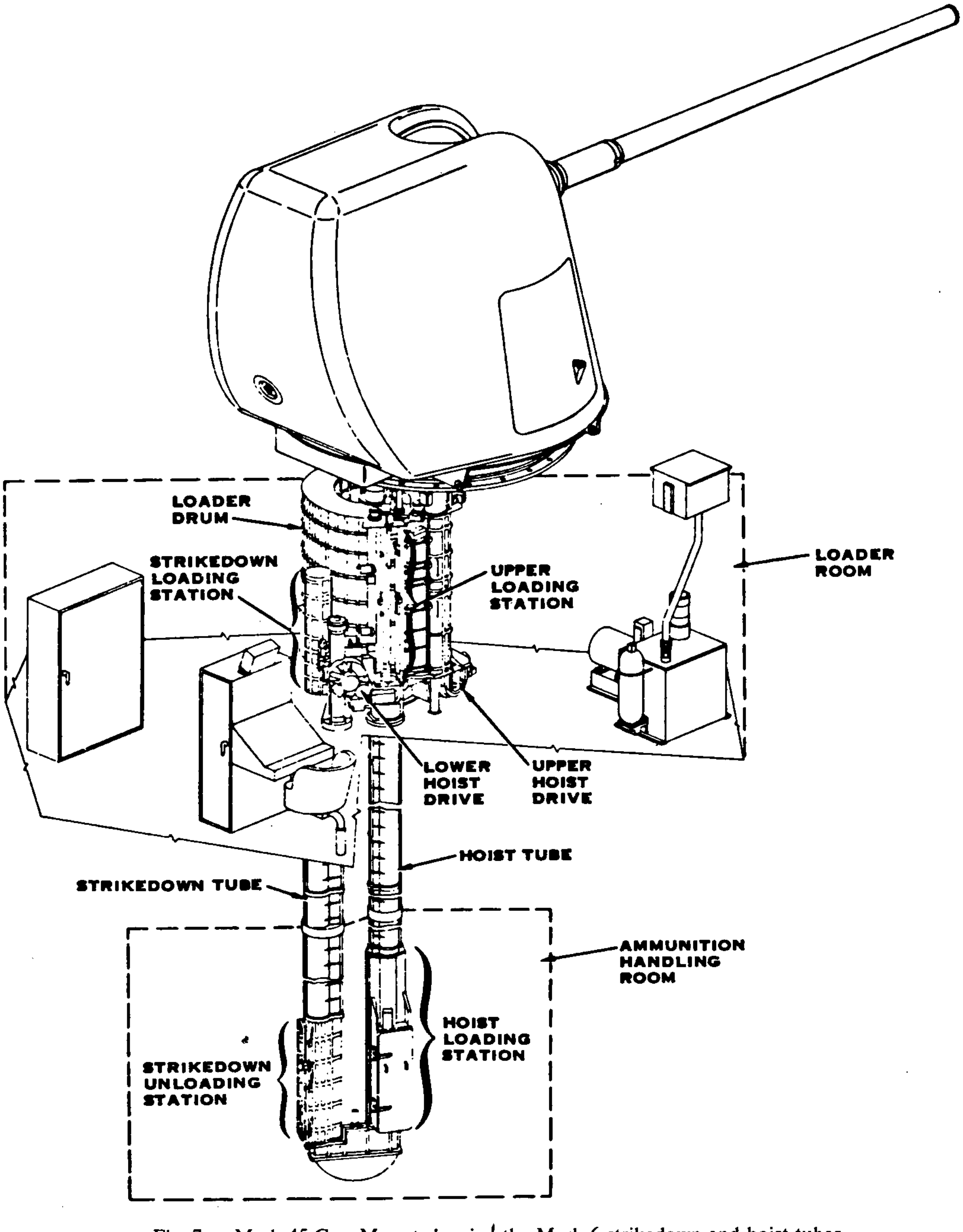


Fig. 7 — Mark 45 Gun Mount showing the Mark 6 strikedown and hoist tubes

ammunition in the Mark 45 Gun Mount. Figure 8 shows candidate weld joints on the flange-to-shell joint. These would consist of simple linear butt welds on 0.179-in. (4.5-mm)-thick Cor-Ten to 1015 steel. The present method used to weld these joints is submerged-arc welding, requiring two passes. Laser-beam welding will require only one pass, with no filler-metal addition or joint-design change. The requirement to grind the weld flush on the inside may also be eliminated. Also, it may be possible to eliminate the use of a fixture, due to the low distortion attributed to the laser weld. Figure 9 depicts estimated cost savings (based on a $56-per-hour labor rate).

Another example is the welding of the inner structure and upper ready-service-ring components on the Mark 13 Guided Missile Launching System, shown in Fig. 10. The inner structure provides the

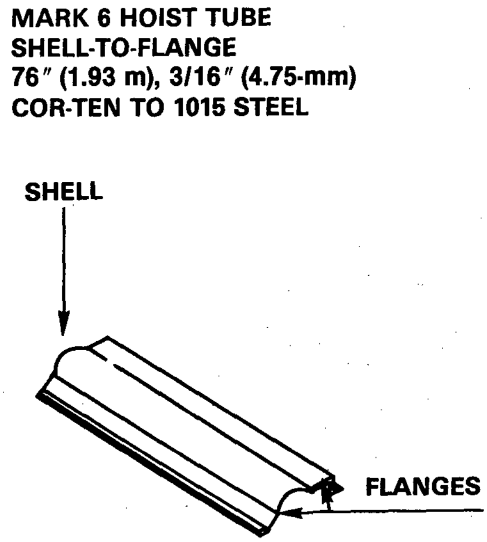


Fig. 8 — Mark 6 hoist tube, shell-to-flange butt weld

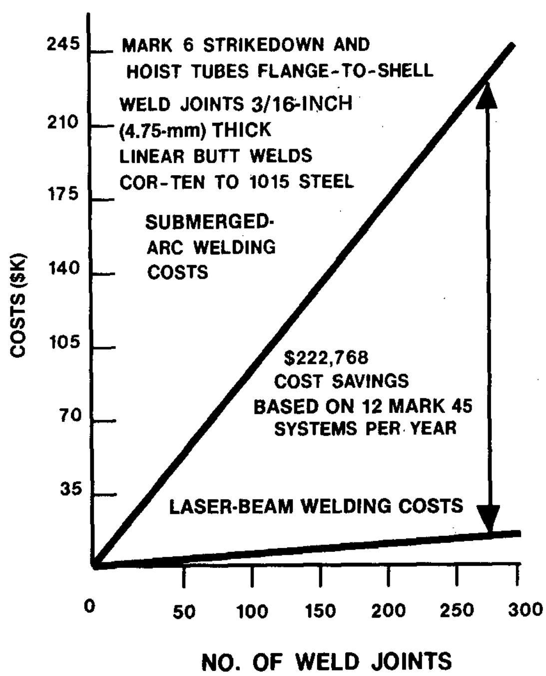


Fig. 9 — Cost savings for the Mark 6 strikedown and hoist tubes

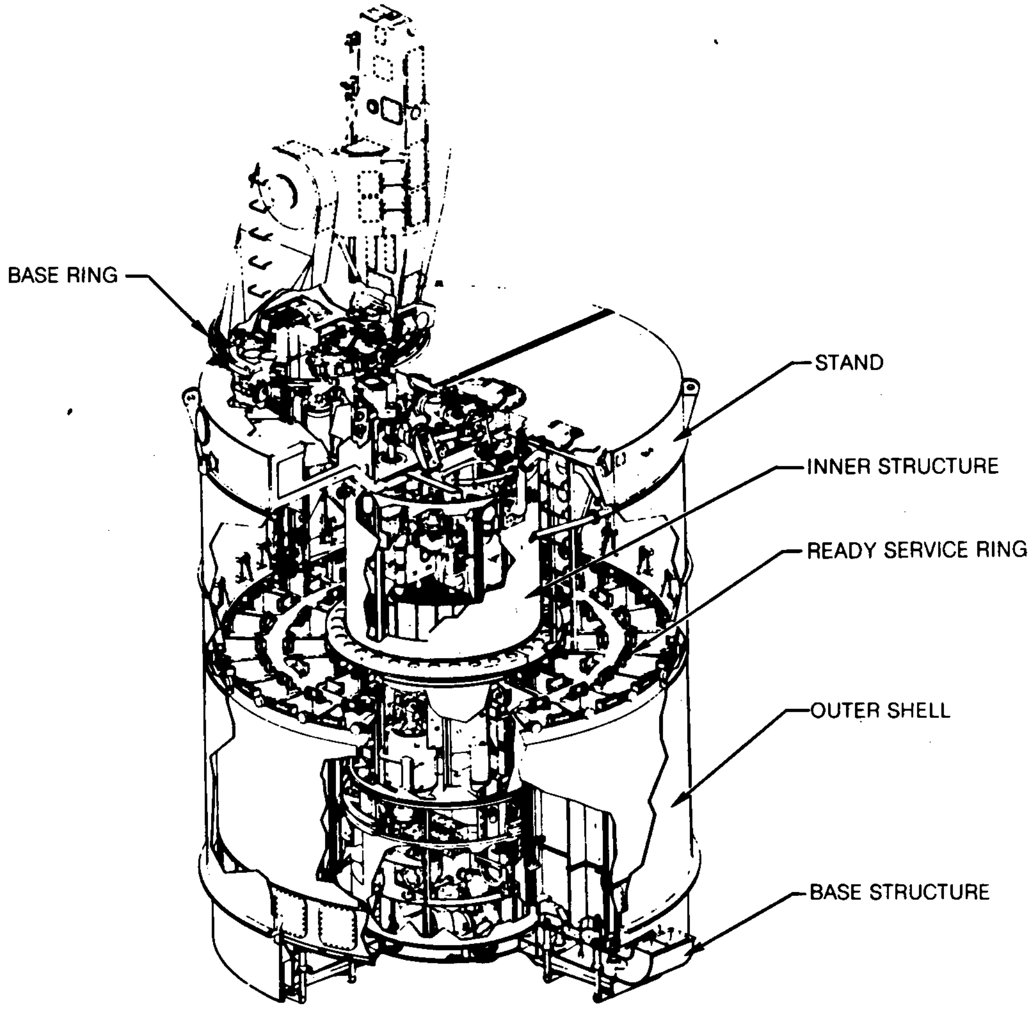


Fig. 10 — Mark 13 Guided Missile Launching System

main housing units for all electrical, hydraulic, and mechanical controls. The upper ready-service ring stores and indexes the missiles. The joints to be laser welded consist of 1/4-in. (6.5-mm)-thick butt-welded shell-to-shell and flange-to-shell joints (Fig. 11). The present welding method is submerged arc, requiring two passes and a back-gouge operation in the flange-to-shell joints. Laser welding will require only one pass, with no filler-wire addition or back-gouge operation. Figure 12 shows the estimated cost savings for laser welding.

The third example of laser-beam welding is on the ready-service-ring components on the Mark 26 Guided Missile Launching System (Fig. 13). The ready-service rings store missiles and transfer them into position for hoisting. The laser-beam welding application is a linear 0.875-in. (22.2-mm)-thick butt weld on the 6- and 10-section ready-service rings. The joints to be laser welded are the flange-to-web joints in 1015 steel (Fig. 14). The present method is submerged-arc welding, requiring seven passes and a back-gouge operation. Laser-beam welding will require only one pass, with no filler-wire addition and no back-gouge operation. Also, grinding and straightening will be reduced due to the noncontact, low-distortion properties of laser welding. Figure 15 shows the cost savings resulting from laser-beam welding.

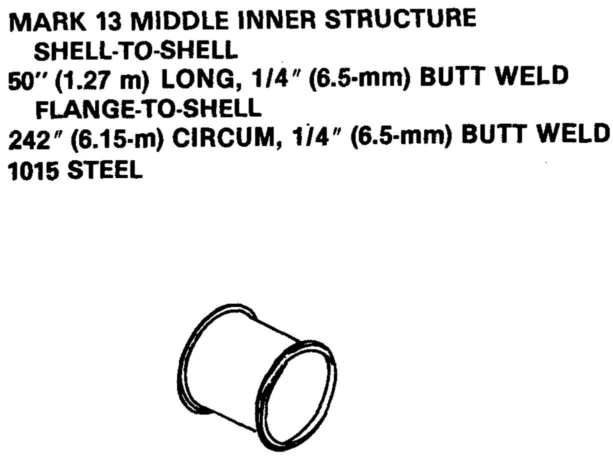


Fig. 11 — Mark 13 middle inner structure, shell-to-shell and flange-to-shell butt welds

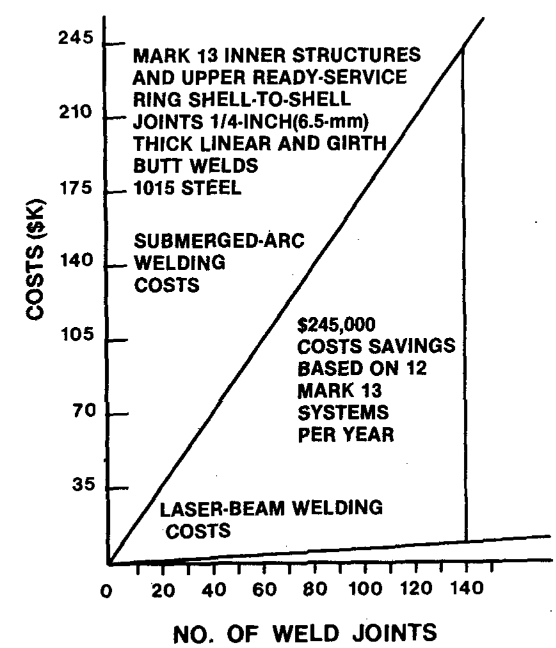


Fig. 12 — Cost savings for the Mark 13 middle inner structure

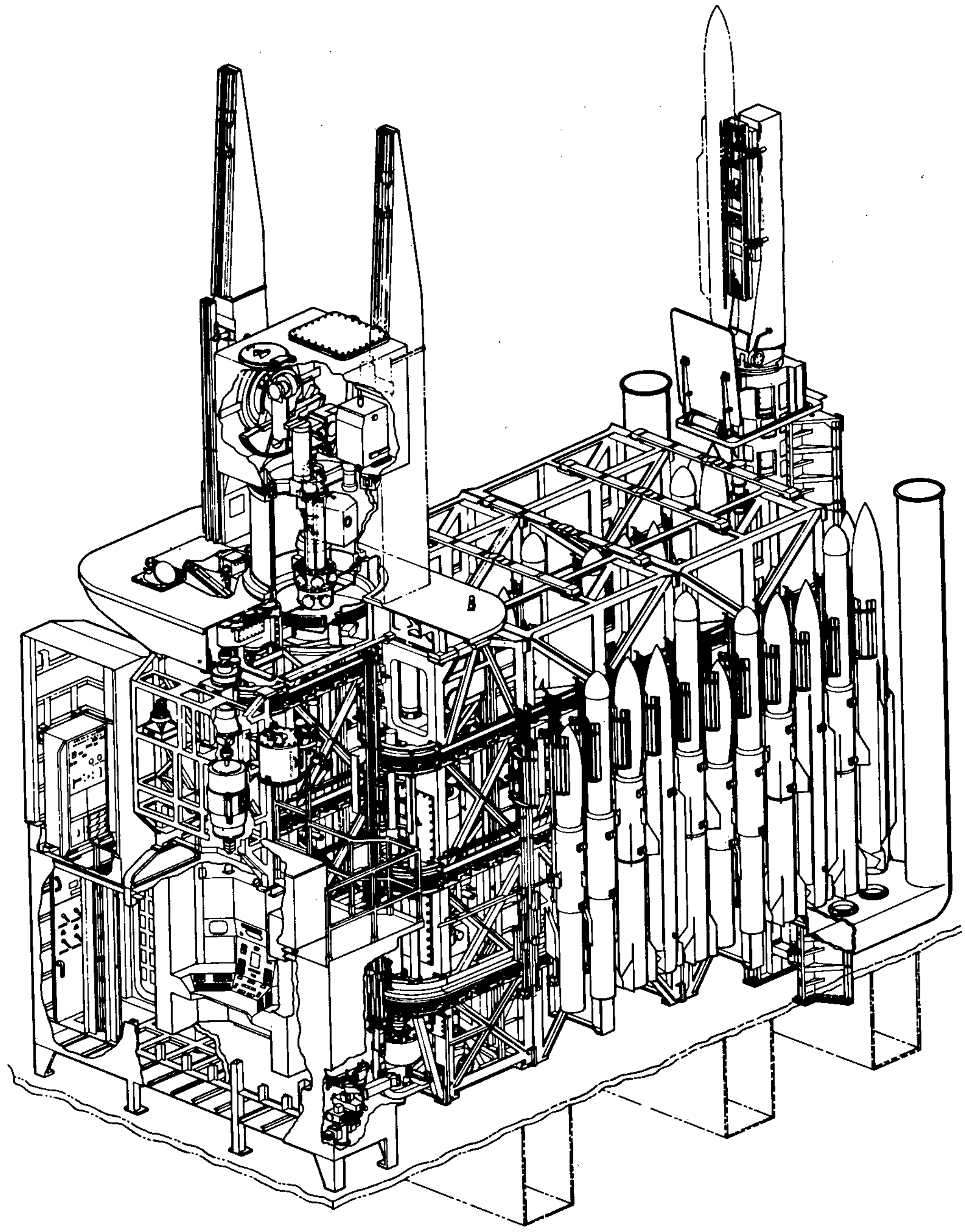


Fig. 13 — Mark 26 Guided Missile Launching System

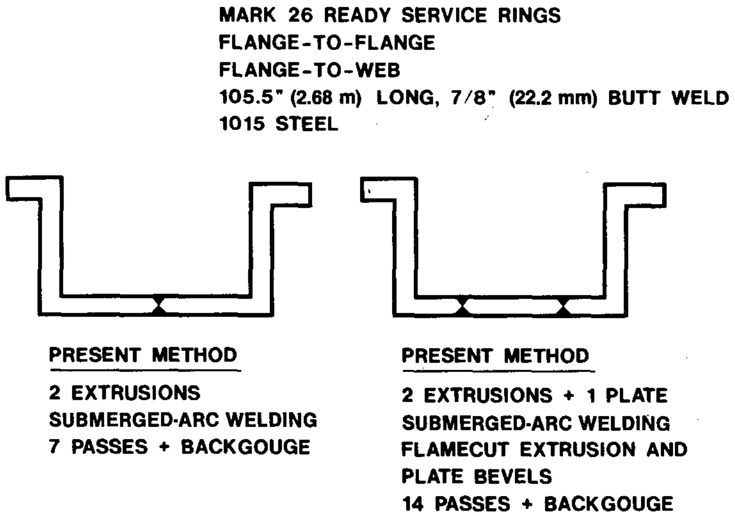


Fig. 14 — Mark 26 ready-service rings, flange-to-flange and flange-to-web butt welds

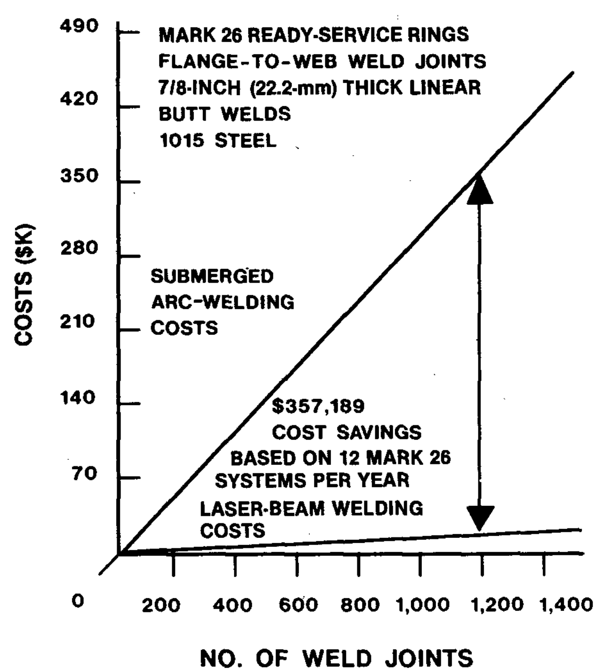


Fig. 15 — Cost savings for the Mark 26 ready-service rings

FUTURE WORK

This implementation of the laser-beam welding system requires an analysis of the factors influencing the physical and functional integration of the system into the production line. Assuming that the laser-beam welding system and the operator are qualified, the successful execution of the following events is required for each candidate laser-beam weld before that joint can be made with the laser:

- Review of necessary weld-joint design changes;
- Preparation of engineering drawings;
- Preparation of alternate process sheets and sketches;
- Selection and design of laser-beam-welding tooling and fixturing;
- Demonstration of laser-beam welding on prototype production model; and
- Production and scheduling of laser-beam welding.

The original economic analysis [13] of laser-beam welding at NIROP, Minneapolis, indicated that whereas the work-station usage would be high, i.e., about 2000 h, the actual laser burn time is low, about 60 h. The implication of this is straightforward: have many work stations. However, the practical implications require a finite number of work stations for welding. Since the laser was purchased and installed, a demand for the use of its unique capabilities as a heat source has arisen in the areas of transformation hardening, alloying, cladding, and cutting. These areas are being examined for potential manufacturing-technology programs.

CONCLUSIONS

A laser-beam welding system has been installed at NIROP, Minneapolis. The laser is a CW, closed-cycle, electric-discharge CO_2 laser, with a wavelength of 10.6 μm, capable of 15 kW at the work station. The work station is a simple linear-traverse table, capable of speeds from 1.7 to 100 ipm (0.7 to 42 mm/s). By use of the beam director, the focal point of the laser can be placed anywhere within a 10-ft × 10-ft × 6-ft (3-m × 3-m × 2-m) volume.

Preliminary laser-beam welds on the material to be welded, ASTM A36, indicate that the weld joint is stronger than the base plate and that the fracture toughness (Charpy V-notch test) is as good as, if not better than, that of the base plate.

The economic analyses show that the savings accrued by laser welding are significant and that the cost of the laser-beam welding system will be recovered within three years. The economic analyses also indicate the potential for time-sharing of the laser among several work stations for welding, heat-treating, alloying, cutting, and cladding.

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